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Improvement techniques of solar still efficiency: A review

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ABSTRACT

A technique used to convert brackish or saline water into potable water is called as solar desalination. The demand of consumable water keeps on increasing due to high population density and automation. Solar energy is used for the conversion phenomenon and the device used for desalination is known as a solar still. Active and passive solar stills are the major types of solar stills. Without the utilization of high grade energy (electrical energy), freshwater is derived from the passive solar still. The yield from the solar still (active or passive solar still) depends upon meteorological, and design and operational parameters. By the mercy of nature, meteorological parameters cannot be controlled by human beings. Many researchers framed mathematical expressions, conducted experiments and validated the outcome from the various types of solar stills by varying the design and operating parameters. The methodologies used in the past years to improve the performance of the active and passive solar stills were reviewed in this paper.

Contents

Abbreviations: PCM, Phase Change Materials; ECM, Energy Storage Material; DEAHP, Double Effect Absorption Heat Pump; MED, Multi-Effect Distillation; LTC, Low Temperature solar Collectors; COP, Coefficient of Performance; PR, Performance Ratio; AHP, Absorption Heat Pump; MSF, Multi-Stage Flash; GOR, Gain Output Rate; TES, Thermal Energy Storage; MSTC, Massive Solar–Thermal Collector; DHS, Domestic Hot Water; SH, Space Heating; LT-MED, Low Temperature Multi-Effect Distillation; TVC-MED, Thermal Vapour Compression Multi-Effect Distillation; CSP, Concentrating Solar Power; IPDP, Integrated Power and Desalination Plants; TSS, Tubular Solar Still; IASS, Inverted Absorber Solar Still; TDS, Total Dissolved Solid; ETC, Evacuated Tubular Collector

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1. Introduction

There is an important need for pure drinking water in many developing countries. Often water sources are brackish (contain dissolved salts) and/or contain harmful bacteria and therefore cannot be directly used for drinking purpose. In addition, there are many coastal locations where seawater is abundant but potable water is not available. Solar desalination is a solar technology with a very long history and installations were built over 2000 years ago, although to produce salt rather than drinking water. The various factors affecting the productivity of solar stills [1–3] are solar intensity, wind velocity, ambient temperature, water–glass temperature difference, free surface area of water, absorber plate area, temperature of inlet water, glass angle and depth of water. The solar intensity, wind velocity and ambient temperature cannot be controlled as they are meteorological parameters. Whereas the remaining parameters, such as free surface area of water, absorber plate area, temperature of inlet water, glass angle and depth of water can be varied to enhance the productivity of the solar stills. By considering the various factors affecting the productivity of the solar still, various modifications are being made to enhance the productivity of the solar still.

Bassam A/K Abu-Hijleh et al. [4] proposed a modified technique to enhance the desalination production by placing sponge cubes over the water surface. The sponge cubes increased the surface area over which the evaporation of water took place and increased the still yield by 18%. Velmurugan et al. [5] increased the exposure area of the water surface using sponges (450 sponges of size $20 \times 35 \times 35$ mm^3) and fins (5 numbers with a size of $900 \times 35 \times 1$ mm^3) in a single basin solar still; the study found that the productivity increases from 1.88 to 2.8 kg/m^2/day. Hiroshi Tanaka et al. [6] theoretically studied the effect of both internal and external reflectors on the amount of solar radiation absorbed by a basin liner as well as on the distillated yield of a single slope basin type still. The inclination of both the still and reflector is advisable, and the productivity is 21% higher than the conventional solar still throughout the year. Kaushal et al. [7] carried out an extensive review on solar stills and highlighted that the solar still efficiency increases by 20% when 1.3 mm cooling film thickness is introduced on a glass cover having a thickness of 5 mm. The annual yield significantly depends on water depth and inclination of condensing cover. In a tilted wick solar still, the daily productivity of the still with reflector increases by 9% as compared to simple solar still. Shukla et al. [8] used jute cloth for increasing the evaporation rate. One end of the jute cloth was dipped into the water reservoir while the surface of the jute cloth was spread over the basin exposed to sunrays. A mathematical model was developed to find the heat transfer coefficients and validated with the experimental values. Rahim [9] proposed an approach in a conventional still to store excess energy during daytime that can be used for continuation of evaporation at night. In the approach, the basin water was divided into evaporating and heat storing zones. The heat storing capacity of the water during daytime was about 35% of the total amount of solar energy entering the still. Hassan et al. [10] conducted an experiment in a stepped solar still with the use of phase change energy storage mixture and also a passive internal condenser in addition to the glass plate condensation. The mixture was an emulsion of paraffin wax, paraffin oil and water in a specific ratio to which aluminum turnings were added to assist in heat transfer by conduction. The design used the latent heat of fusion of the mixture for obtaining continued desalination even after sunset. Results indicated that the use of the energy storage material led to a larger improvement in still yield of 5.2 kg/m^2/day. Kalidasa Murugavel et al. [11] conducted experiments on a double slope simulation type solar still with a thin layer of water in the basin. For maintaining the thin layer of water in the basin, the water was spread throughout the basin by some kind of wick or porous materials. Experimental results of still yield by using wick materials, light cotton cloth, light jute cloth and sponge sheets of small thickness and porous materials like washed natural rock of small sizes were compared. The result showed that the still with a black light cotton cloth as spread material was found to be more productive. El-Sebaii et al. [12] studied the performance of a single slope still with Phase Change Materials (PCM) as a storage medium and found that after sunset, the PCM acts as a heat source for the basin water until the early morning of the next day. The result showed that there was a decrease in the output at daytime but an increase in productivity at nighttime. The double production of pure water on a summer day with a daily efficiency of 84.3% was achieved by the PCM incorporated solar still. Voropoulos et al. [13] coupled a conventional solar still with a solar collector field along with a hot water storage tank and conducted experiments. The result showed that the output of a conventional solar still is significantly increased if it is coupled with a solar collector field and a hot water storage tank. Draw-off of hot water volume equal to 1/4, 1 /2 or 1 tank volume reduces distilled water output by 36%, 57% or 75%, respectively and energy output during the distillation is about 1900, 3300 and 5200 MJ. Tiwari et al. [14] attempted to find out the effect of water depth on the evaporative mass transfer coefficient for a passive single-slope desalination system in summer climatic conditions. They conducted an experiment on a south facing, single slope, solar still of 30° inclination of condensing cover, for 24 h on five different days for five different water depths from 0.04 m to 0.18 m. The study leads to the conclusion that the convective and evaporative heat transfer coefficients are important for varying water depths to optimize the same for the highest yield. The fluctuations in the value of convective heat transfer coefficient from water to condensing cover, as observed for lower water depth, reduce with the increase in water depth. Janarthanan et al. [15] derived an expression for flowing water, glass, tilted-wick water surface and floating-wick water surface temperature and efficiency of the floating cum tilted-wick type solar still. The result showed that glass cover temperature decreases significantly due to the water flowing over the glass cover which causes fast evaporation during peak sunny hours. The effect of water flowing over the glass cover has a fascinating role on the performance of the still. An attempt was made by Dimri et al. [16] to evaluate inner and outer glass temperature and its effects on productivity. The effect showed that higher yield was observed for an active solar distillation system as compared to the passive mode due to higher operating temperature differences between water and inner glass cover. The yield decreases with increase in glass cover thickness and the

convective heat transfer coefficient increases with increase in wind velocity. Qiblawey et al. [17] described various desalination technologies suitable for use in remote areas such as the direct method and indirect method. The direct method is used to produce distillate directly in the solar collector for a small water demand. The indirect method consists of several techniques like multistage flash desalination, vapour compression, reverse osmosis, membrane distillation and electrodialysis.

In this regard this paper aims to review the various methods used to improve the efficiency of the solar still.

2. Techniques used to improve the performance of the solar still

The performance of the solar still is affected by design, operational and meteorological parameters. Here, the research work carried out to improve the performance of the solar still and new techniques endeavored to get better performance were reviewed. This paper is largely classified into discussions on energy storage material incorporated in the solar still, modification done on the glass cover inclination of the solar still, conventional solar still coupled with solar collector, solar still combined with external reflector, sun tracking system used to receive effective solar insolation, solar still inherent better basin liner material, introducing vacuum technique and other novel practices on solar stills.

2.1. Energy storage materials

Solar energy is an abundant and safe source of energy and therefore is recognized as one of the most promising alternative energy options. However solar energy is intermittent by nature as there is no sun at night. Its total available value is seasonal and is dependent on the meteorological conditions of the location. Hence, solar energy presents an unsteady energy resource. So, thermal energy storage will be necessary to save the available solar energy at a period of no load or when excessive energy is available and to make up for the shortage of energy when the load is in need of energy.

2.1.1. Baffle suspended absorber plate

The evaporation rate of saline water increases with the temperature of the saline water and it is proportional to the temperature of the free surface area of water only. Baffle suspended absorber plates are used to increase the free surface area of the water.

El-Sebaii et al. [18] designed and fabricated a single slope single basin solar still with aluminum movable baffle suspended absorber plate as shown in Fig. 1. The experimental and theoretical investigations were made by the suspended absorber plate with and without vents. The performance of the modified still was compared with the conventional solar still. The movable plate divides the basin water into upper and lower portions. The absorbing surface facing the sun is painted black with an ordinary black paint to maximize the fraction of solar radiation absorbed by it. An ordinary glass of thickness 0.003 m inclined to an angle of 15° with respect to the horizontal plane is used as the still cover. Heat losses from the sides and back of the solar still are minimized by providing 0.075 m thick layer of sawdust. The daily productivity of the modified solar still is increased from 4.736 to 5.737 kg/m^2/day compared to the conventional solar still. This is because of the modified solar still which operates at higher temperature and the lowest possible mass of water column is advised to achieve high productivity.

2.1.2. Charcoal particle

Naim et al. [19] constructed non-conventional solar stills with charcoal particles as the absorber medium and investigated factors such as range of charcoal particle, saline water flow rate and glass cover inclination. The solar still basin area is 0.5 m^2; at the bottom of the solar still 0.05 m thickness sawdust is spread uniformly above which a plastic sheet is placed. Charcoal particles of uniform size are placed uniformly onto the plastic sheet as a layer of 0.02 m thickness. A glass plate (0.003 m thick) is made to cover the whole surface of the plastic box which is 0.03 m above the charcoal bed. The still is placed on a wooden base of variable inclination to the horizontal. Charcoal with particle sizes 0.0015, 0.005 and 0.007 m was studied with different flow rates of saline water ranging from 40 to 160 ml/min. Experimental results showed that coarse charcoal granules give acceptable results at high flow rates followed by intermediate then fine granules. A 15% improvement in productivity was achieved over the wick type solar still.

2.1.3. Packed layer

Zeinab et al. [20] modified the conventional solar still with the packed layer that was installed at the bottom of the basin to increase the efficiency of the still. A packed layer is formed from glass ball which is considered as a simple thermal storage system. The packed layer is composed of glass balls of 13.5 mm diameter which covers the surface of bottom of still basin. The material of the packed layer has higher thermal properties. Due to the solar energy stored inside the packed layer during sunrise, the water temperature of the modified still increases. Therefore, a packed layer helps the heating operation of still water throughout daytime and after sunset to increase freshwater productivity. The efficiency of the modified solar still using packed layer thermal energy storage was increased by 5% in May, 6% in June, and 7.5% in July.

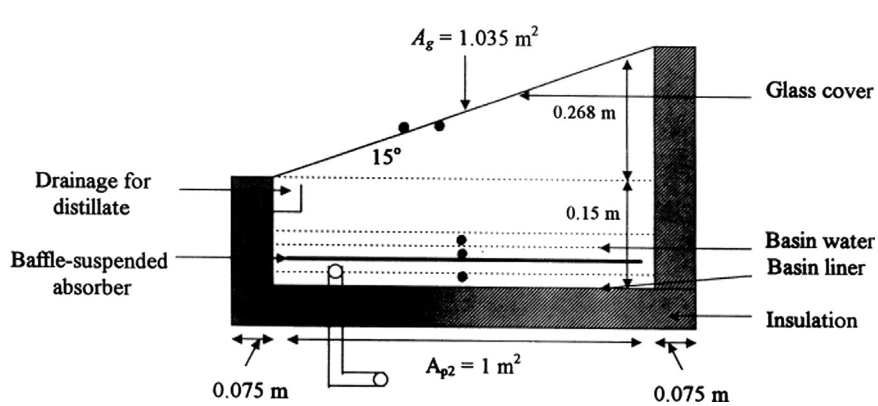

Fig. 1. A schematic diagram of the single slope single basin solar still with baffle suspended absorber plate [18].

2.1.4. Integration of storage tank

Incorporation of a storage tank with a solar still leads to higher distilled water output due to higher basin water temperatures. Voropoulos et al. [21] investigated the behavior of a conventional type solar still coupled with hot water storage tank (Fig. 2) by keeping the tank water temperature constant at different levels. The bottom of the black basin before and after modification has an area of 12.5 m^2, which is parametrically insulated and is made of aluminum. A water storage tank is integrated below the solar still. The tank is made of aluminum, insulated exactly the same way as the basin of the still at the bottom and sides, whereas the height of the tank is 30 cm, resulting in a tank volume of 3.75 m^3. Heating of the tank water is done through a fin-and-tube heat exchanger placed inside the tank, using an electric heater. The heating installation is equipped with a temperature regulating device to keep the tank water temperature almost constant in the desired limits. Tests have been conducted in the compact solar still–storage tank distillation system for several days by keeping the tank water temperature at different levels, such as 70 °C, 60 °C, 50 °C and 40 °C. The experimental work was carried out in day as well as in night session.

The observations made during this investigation were that solar still–storage tank systems lead to higher distilled water output, due to higher basin water temperature as a result of hot storage tank water. The hot water storage tank acted as the heat-collecting unit and the solar still served only as the condensation unit. The distillate output was able to remain constant throughout the whole day by integrating the storage tank with the solar still.

2.1.5. Phase Change Materials

In latent heat storage, the principle is that when heat is applied to the material it changes its phase from solid to liquid by storing the heat as latent heat of fusion or from liquid to vapour as latent heat of vaporization. When the stored heat is extracted by the load, the material will again change its phase from liquid to solid or from vapour to liquid.

Naim et al. [22] enhanced the productivity of the solar still by the usage of an Energy Storage Material (ESM). During the still assembly itself the ESM is placed in its tray. A specially formulated mixture consisting of an emulsion of paraffin wax, paraffin oil and water to which aluminum turnings are added to promote heat conduction is used effectively to store heat in the daytime, and then give off its heat at nighttime. In total, 8 experiments were conducted. The productivity was increased from 203 ml/m^2h to 256 ml/m^2h when the duration of the experiment was extended to 2 h in the evening session. By the usage of 500 ml distilled water as the energy storage material the productivity reached a level of 299 ml/m^2h. The mixture of paraffin wax, paraffin oil and water with added Al turnings used as a special phase change material increases the productivity to the maximum value of 851 ml/m^2h when the supply of saline water is 40 ml/min.

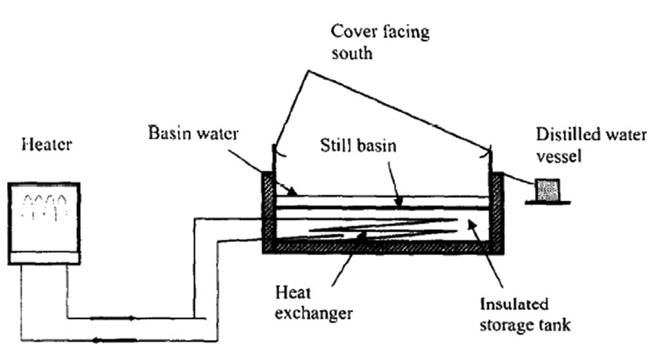

Fig. 2. Schematic diagram of the solar still–storage tank distillation system [21].

2.1.6. Black rubber and gravel

Nafey et al. [23] improved the distilled water productivity of the single basin solar still by using black rubber with thicknesses of 2, 6, and 10 mm and black gravel of sizes 7–12, 12–20 and 20–30 mm. The experimental work was conducted with different brine volumes (20, 30, 40, 50 and 60 l/m^2) at a glass cover angle of 15°. The use of black rubber material of 10 mm thickness within the solar still basin increases the productivity by 20% at the conditions of brine volume 60 l/m^2. The enhancement of the productivity is because of the stored energy in the rubber and the energy lost through the base is conserved in the basin water. The black gravel absorbs and releases the incident solar energy faster than the black rubber. In addition, black gravel with sizes 20–30 mm increases the productivity by 19% at the conditions of 20 l/m^2. This is because of the capability of the large gravel size to absorb a large amount of the incident solar energy. The spaces between the large sizes of gravels are considerably wider which are occupied by a large amount of water. A thin layer of water above the black gravel leads to an increase in the evaporation rate.

2.1.7. Black rubber mat, black ink and black dye

Experimental evaluation of a single basin solar still with double slopes and an effective still area of 3 m^2 using different absorbing materials such as black rubber mat, black ink and black dye was done by Akash et al. [24]. The glass plate inclination is maintained at 25° and 120 l of saline water is kept in the basin. The lowest production rate occurred when water alone was used and there was no other absorbing material inside the still. The productivity was enhanced by 38%, 45% and 60% respectively when the absorbing materials black rubber mat, black ink and black dye were used. The result indicates that black dye-in-water solution can absorb solar radiation at higher rates than other materials like black ink-in-water and black rubber sheet.

2.1.8. Jute cloth

Jute cloth has a good porous structure to absorb water. In addition, the thread created from jute is quite strong and it is the cheapest of available natural fibers. It has exceptional insulating properties, low thermal conductivity and moderate moisture regaining capacity. Thermo-physical characteristics of jute cloth are given as density 1080 kg/m^3, heat capacity 1.25 kJ/kg K and thermal conductivity 0.11 W/m K.

Sakthivel et al. [25] experimentally studied the regenerative solar still with jute cloth (Fig. 3) as an energy storing material. The jute cloth absorbs the heat from air-vapour mixture. The temperature of the air-vapour mixture in the regenerative solar still is reduced and becomes lesser than the temperature in the conventional still. The latent heat released from the glass cover is utilized for the evaporation of water from the jute cloth. Hence, the still hourly yield increases and temperature of the bottom of the glass cover gets reduced than in the case of conventional still. While absorbing the latent heat of condensation, some of the solar radiation falling on the saline water gets intercepted by the jute cloth. So when compared with the conventional still, the temperature of the saline water in the regenerative still is lesser than the saline water temperature of the conventional still. The regenerative still with jute cloth gives cumulative yield and efficiency of 20% and 8% respectively which are higher than those of conventional solar still.

2.1.9. Sensible storage medium

A mathematical model was generated for an active single basin solar still with a sensible storage medium as sand under the basin liner of the still by El-Sebaii et al. [26]. The optimum value of basin liner thickness was found to be 0.003 m. The daily productivity and

efficiency of the still decreases with increasing the mass of the sand and thermal conductivity of the basin liner. The solar still without sensible storage medium gives daily productivity and efficiency of 2.852 kg/m^2/day and 27%. After sunset, sand acts as the heat source for the basin water until the early morning of the next day; therefore, by the addition of 10 kg of sand the daily productivity and efficiency increase to 4.005 kg/m^2/day and 37.8% respectively.

2.1.10. Absorbing materials

Salah Abdallah et al. [27] tried three absorbing materials (Fig. 4) namely coated and uncoated metallic wiry sponges and volcanic rocks on three stills and the effect of the still on the yield was compared with a fourth one which was kept as the reference still. Impressive superior properties such as absorptivity, permeability and extinction of metallic wiry sponges made it suitable to be used as an absorbing material in solar still. The overnight outcome showed that coated metallic wiry sponges increased yield by 28%, uncoated metallic wiry sponges increased productivity by 43% and volcanic rocks enhanced the performance by 60%.

2.2. Glass cover inclination

The evaporated water vapour from the basin still strikes the inner surface of the glass cover and condenses. The condensate flows along the inclined glass plate and is collected in a trough which is fitted at the bottom edge of the glass cover plate. The condensate thus collected is free from all kinds of impurities. Glass cover inclination is one of the important parameters which determines the performance of the solar still.

A thermal analysis of solar desalination was developed by Tiwari et al. [28] to optimize the inclination of the glass cover for maximum yield. The effects of inclination on the internal heat and mass transfer relation, and water and glass cover temperature were also studied. The valuable points observed from the research work are that the yield increases with increase of inclination in winter and vice-versa in summer. Due to the increase of inclination in summer and winter a significant reduction in evaporative heat transfer coefficient was observed. During summer to produce maximum yield, the optimum inclination of the glass cover should be 10° for Delhi's climatic conditions and this angle is larger for winter conditions.

The investigation byAbdul Jabbar [29] gives the detailed effect of the cover tilt angle on productivity. A relation between the cover tilt angle and productivity of simple solar still in various seasons is established together with a relation between the optimum tilt angle and the latitude angle. The salient output from the research is that the increase of the tilt angle results in increased thermal losses from the cover and decrease in the yield because of the increased reflected radiation. If the angle is low some droplets may fall due to the speed at which the droplets travel along the interior surface of the cover towards the collecting tray.

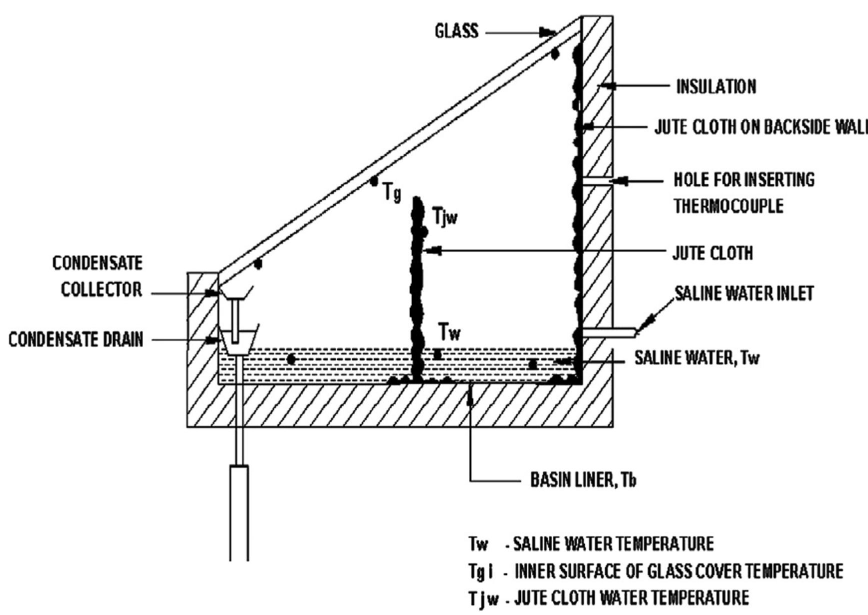

Fig. 3. Schematic diagram of a single slope solar still with vertical jute cloth [25].

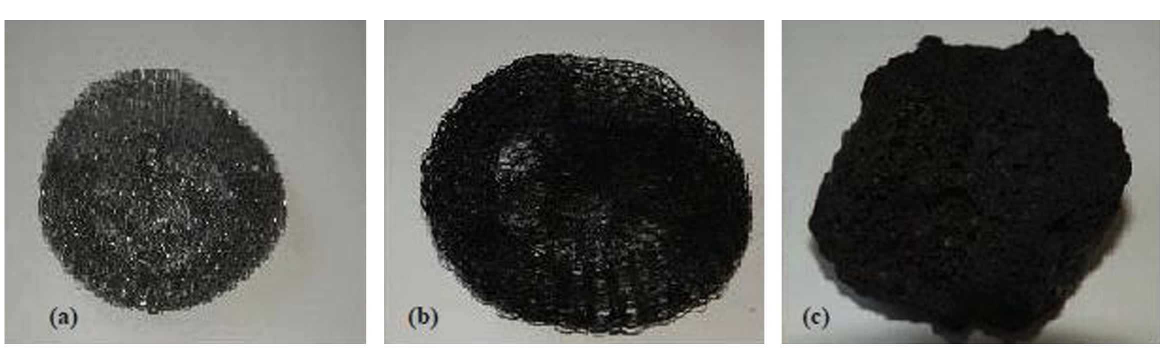

Fig. 4. Various absorbing materials used in solar stills (a) uncoated metallic wiry sponge (b) coated metallic wiry sponge, and (c) black volcanic rocks [27].

2.3. Vacuum technique

By generation of vacuum inside the solar still, water can be quickly evaporated at much lower temperatures which demands lesser energy than conventional techniques.

Al-Kharabsheh et al. [30] studied and tested an innovative water desalination system using low-grade solar heat. The atmospheric pressure and gravity were used to create a vacuum distillation. The system consists of a solar heating system, evaporator and a condenser at a height of about 10 m above the ground level, connected via pipes to a saline water supply, concentrated brine discharge, and a freshwater tank. By balancing the hydrostatic and the atmospheric pressures in the supply, discharge pipes vacuum is generated. For the same input, the performance of the system is better than the flat basin solar still. The vapour pressure of seawater is about 1.84% lesser than that of freshwater over the temperature range of 0–100 °C. At a water depth of 0.04 m, the maximum collector outlet temperature reaches about 61.2 °C and the water temperature is about 45.6 °C, the maximum evaporation rate is about 5.1×10^{-5} kg/s and the accumulated output for water is about 1.3 kg and the pressure reaches a maximum value of about 4.7 kPa absolute. The modified system result reaches up to 6.5 kg/m^2/day whereas the conventional system gives only 3–4 kg/m^2/day.

Nassar et al. [31] examined the productivity of solar desalination system working on the basis of evacuation. The solar intensity concentration was done using a concave mirror and the experimental model consists of elliptical, metallic container located in the focus of concave reflector. To reduce the normal boiling point of the incoming water a vacuum in the order of 25 kPa was generated. The water productivity of the modified solar still was found to be about 20 l per day per unit area of the reflector which is around 303% higher than that of other thermal solar stills and the performance ratio is 900% more than the roof-type desalination solar systems. 90.1% power reduction is achieved to produce 1 kg of freshwater.

Theoretical analysis was made for single stage and two stage solar driven flash desalination system based on passive vacuum generation by Maroo et al. [32].The system uses the natural forces of gravity and atmospheric pressure to create a vacuum. In this test matrix, for the case of constant temperature heat source the single stage system produces distillate and performance ratio as 11.31 kg and 0.746 respectively, whereas in the double stage system the values are 13.9 kg and 1.42 in 12 h. With the incorporation of solar collector with solar still, the single stage system produced distillate of 5.54 kg in 7.83 h with a performance ratio of 0.748. Meanwhile, two stage system turned out 8.66 kg in 7.7 h freshwater with a performance ratio of 1.35.

2.4. Wick materials

Water depth is inversely proportional to the productivity of still. If the water surface in the basin is exposed to a larger area, the evaporation rate is high. The water surface can be increased by employing suitable wick material in the basin.

Kalidasa Murugavel et al. [33] studied the performance of basin type double slope solar still with different wick materials (Fig. 5a) like light black cotton cloth, light jute cloth, sponge sheet, coir mat and waste cotton pieces. From the different basin wick materials, light black cotton cloth was the most effective which yielded higher production per day. With different fin configurations in the basin (Fig. 5b), the aluminum rectangular fin covered with cotton cloth and arranged in lengthwise direction was more effective and gave slightly higher production than the light black cotton cloth.

A modified design of solar still was tried by Kabeel [34]. It consists of a pyramid shaped top surface with four glass covers. To increase the evaporative surface area, black paint coated jute wick is used. The average distillate productivity of the modified still during the 24 h time is about 4.0 l/m^2 and its efficiency reaches about 45%. The estimated cost of one litre from the present still equals 0.065$ whereas the cost of one litre from a conventional solar still is around 0.083$.

An analytical expression for the thermal efficiency of evaporative heat loss and heat transfer for an open- and closed cycle systems of floating cum tilted wick solar stills in terms of system design and climatic parameters was derived by Janarthanan et al. [35]. It was found that the efficiency of the closed-cycle system was maximum for a low flow rate of water. The variations of the instantaneous efficiency of an open cycle system with relative humidity depend on the total heat transfer coefficient, from the wick surfaces to ambient.

2.5. External reflector

The external reflectors used in the solar still are made up of highly reflective materials such as mirror finished metal plate. The direct and diffuse radiation transmitted through the glass cover is enhanced by the application of the external reflector.

A theoretical analysis was made on tilted wick solar still with external flat plate reflector with the aim of determining optimum inclination for reflector and solar still for different seasons by Hiroshi Tanaka [36]. The results showed that the daily amount of distillate can be increased by inclining the reflector backwards in winter and forwards in summer. The inclination angle of the reflector would be less than 25° throughout the year. By adjusting the inclination of both the still and reflector in any season the efficiency increases on average by 21% throughout the year than a conventional tilted wick still.

Abdul Jabbar et al. [37] experimentally investigated the productivity of a basin type solar still with internal and external reflector (Fig. 6) tilted at an angle of 0° (vertical), 10°, 20° and 30°, with a latitude angle of 33.3° N during winter. The still cover angle was varied by 20°, 30° and 40°. The investigation reported that the daily yield of the still with no reflectors would remain almost the

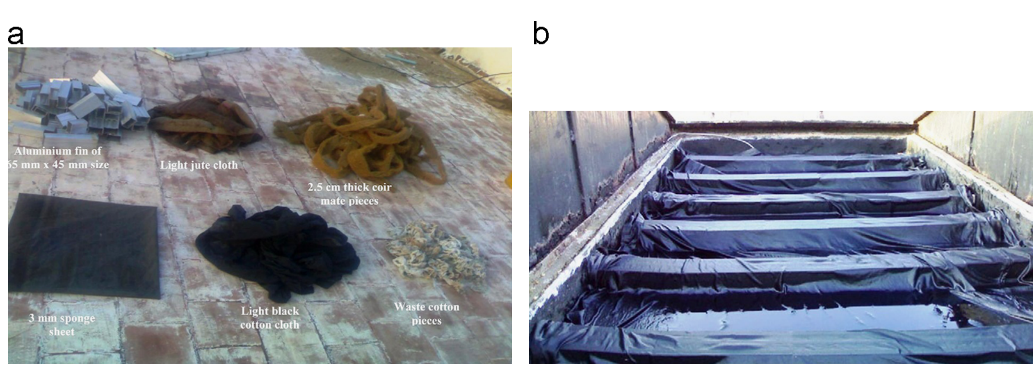

Fig. 5. (a) Different wick materials [33]. (b) Photograph of the still with aluminum fin covered with black cloth in the basin [33].

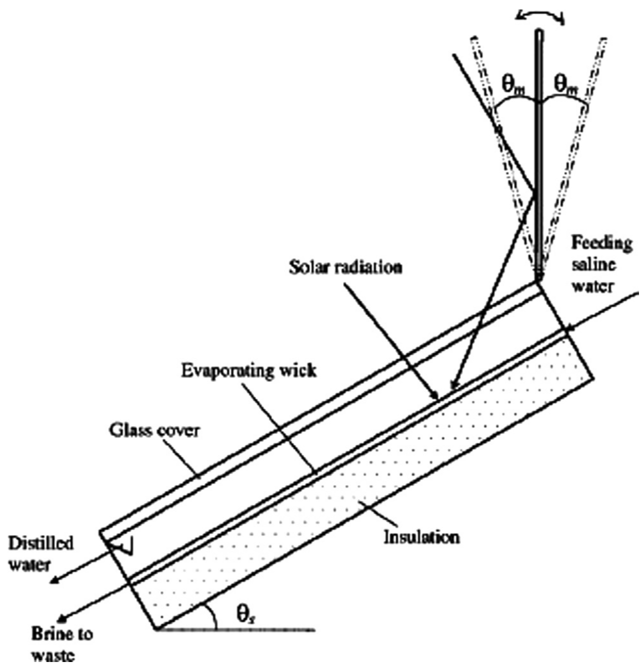

Fig. 6. Schematic diagram of a tilted wick solar still with external reflector which can be inclined backwards or forwards [36].

same at any glass cover angle. The most productive solar still in winter is a still with a cover angle of 20° and an internal and external reflector inclined at 20° and its productivity will be around 2.45 times that of simple still with no reflectors.

2.6. Sun tracking system

The main drawback of a conventional solar still is that the amount of distilled water produced per unit area is low. The key objective is to improve the performance of the conventional solar still through the combined functioning of the solar still with a sun tracking system to increase the solar still capability to capture more solar radiations.

A case study was carried out by Garcia-Rodriguez et al. [38] in multi-effect distillation or multi-stage flash plant with a performance ratio of 10 and coefficient of heat pump 2. The author suggested that, at Spanish conditions direct steam generating parabolic troughs are more suitable when compared to other collectors like salinity-gradient solar ponds, flat plate collector, evacuated tube collectors and compound parabolic collectors. The percentage increase of freshwater production of direct steam generation compared to conventional parabolic trough collector lies between 18% and32%. The stationary solar still performance was also compared with a one axis sun tracking system coupled with heat pump. The direct steam generation using seawater or brine is a promising technique for solar multi-stage flash plants.

Salah Abdallah et al. [39] did three modifications in single slope solar still such as (i) introducing reflective mirrors on all interior sides of the still in order to reduce the heat losses, by which the productivity increased to 30%, (ii) introduction of a stepwise basin instead of conventional flat basin which in turn causes 40% increase in surface area that leads to increased heat transfer, by which enhancement in the productivity is improved to 180%, and (iii) introduction of sun tracking system to sense the direction where the solar intensity is maximum thereby improving the productivity of absorption by 380%.

A computerized sun tracking device was used for rotating the solar still with the movement of the sun by Abdallah et al. [40]. By using the sun tracker the water temperature increases, and the thermal capacity of the water decreases, by which the evaporation rate increases, hence it leads to improved productivity. A comparison between fixed and sun tracked solar stills showed that the use of sun tracking increased the productivity for around 22% due to the increase of overall efficiency by 2%.

2.7. Basin liner material

The incident radiation transmitted through the glass cover is absorbed by the basin liner material. The energy absorbed at the base is largely transferred to the water in the still and a small fraction of it is lost to the ambient by conduction through the base.

A solar still with a basin size of $0.73 \times 0.73\ m^2$ was used to achieve a fluoride reduction of 92–96% as compared to the untreated samples by Sahoo et al. [41]. The still was tested on five different modes. In the first three modes, the basin water capacity is varied as 10, 15, 20 l and the efficiencies are 7.28%, 7.78% and 8.1% respectively. In the fourth mode blackened basin liner was used and still efficiency increased by 4.69%. When the basin is modified by a blackened base liner with bottom and side thermocol insulation of 20 mm thickness it produced 6.05% efficiency in the fifth mode.

Asphalt liner and sprinkler were adopted to enhance the productivity of the single slope solar still by Badran [42]. The introduction of asphalt as basin liner increases the output by 29% when compared to the usage of black paint as the liner. The usage of sprinkler (cooling film) on the glass cover increases the temperature difference between glass and water which in turn contributes to 22% increase in output. It is also found that productivity increases with a decrease in the depth of water and an increase in wind velocity up to a typical velocity; after that, it starts decreasing.

2.8. Solar collector incorporated desalination system

Schwarzer et al. [43] numerically investigated and found that the solar collector combined with desalination tower produces 25 l/m^2/day. The desalination tower is made of six stages. The modified solar desalination system output is five times greater than the conventional basin type solar desalination system. The solar collector area 2 m^2 with 50% efficiency and tray size of $0.8 \times 0.8\ m^2$ are the suitable data taken for the simulation work. The desalinated water was subjected to laboratory tests and it was found that it was free from coliform group bacteria.

Dwivedi et al. [44] validated thermal modeling of a double slope still integrated with flat plate collector in such a way that the hot water from collector plate enters into the basin under natural circulation. The double slope active solar still under natural modes gives 51% higher yield in comparison to the double slope passive solar still. The thermal efficiency of double slope active solar still is lower than the thermal efficiency of double slope passive solar still. However, the exergy efficiency of double slope active solar still is higher than the exergy efficiency of double slope passive solar still. The daily yield of a double slope passive solar still for a particular day in the month of March 2008 was found to be 1.838 kg/m^2 whereas the daily yield of a double slope active solar still under natural mode was found to be 2.791 kg/m^2.

A two-stage low temperature desalination process was developed and tested at a field site in the Puget Sound bay area of the State of Washington by Gude et al. [45]. In this double stage configuration, the specific energy consumption of the process was 1500 kJ/kg (1500 MJ/m^3) of the thermal energy and it is less than 3.6 kJ/kg (1 kW h/m^3) of mechanical energy. Economic analysis was conducted on the process with (i) heat energy from a cheap waste heat source and (ii) a solar powered heat source. By using a cheap waste heat source of cost $0.5/GJ, the required desalination

cost is only \$3/m^3. When the desalination plant is coupled with low grade flat plate solar collector then the production cost is less than \$7/m^3.

Gude et al. [46] designed a low temperature desalination system to produce 100 l /day of freshwater. A solar collector area of 15 m^2 with 1 m^3 of Thermal Energy Storage (TES) volume or 18 m^2 with 3 m^3 of TES volume is required to generate the freshwater. This additional area of the solar collectors helps the TES to accumulate the excess energy which can be stored and supplied on a cloudy day or low solar insolation day. A margin of estimated cost of the low temperature desalination system with thermal energy storage system is \$655 higher than that without thermal energy storage system.

A critical literature review work was carried by Matteo D'Antoni et al. [47] in the Massive Solar–Thermal Collector (MSTC). The heat transfer and storing phenomena, moisture transfer phenomena and frost formation characteristics are taken in the MSTC review work. Compared to traditional flat plate collectors, MSTCs behave similarly to these in low temperature range (delivered fluid temperature $<50\,^{\circ}$C) and the share of solar energy is dependent on several aspects, such as building loads, solar availability and plant scheme solutions. The MSTC applications were studied in recent works mostly and were applied in those cases where Domestic Hot Water (DHW) and Space Heating (SH) demands were present.

The evacuated tube collector model solar water heater coupled with a still is shown in Fig. 7. Sampathkumar et al. [48] conducted a performance study on various days at different timings. The main objective of the research was to effectively utilize the solar water heater for solar still productivity enhancement and it is working as a hybrid system. It was found that the productivity of the coupled solar still was doubled when compared to the simple solar still. The modification increased the yield by 77%, even if the collector and solar still were coupled only after the storage tank water temperature reached 60 °C.

A parabolic trough solar collector was employed with outlet temperature less than 100 °C to drive the proposed seawater humidification–dehumidification desalination system by Mohamed et al. [49]. The collector thermal efficiency value increases with the increase of the solar radiation until it reaches a maximum value and then declines. The productivity of the desalination system increases with the increase of the daytime till an optimum value and then decreases. The production time reaches a maximum value of about 42%, 37%, 33% and 29% during summer, spring, autumn and winter respectively.

2.9. Humidification–dehumidification principle desalination system

A new type of seawater desalination plant using solar energy was fabricated and dynamic simulation program (TRNSYS) was carried out by Chafik [50]. The plant capacity was designed to get 10 m^3 of potable water daily. The solar energy was used to heat the air stream and then hot air was humidified by seawater, followed by dehumidification to derive potable water from it. To minimize the overall running cost of the desalination plant, development of each equipment like collector, humidifier and dehumidifier was done and optimization was also carried out. Three different types of collector, high-efficiency polycarbonate, low-cost, low-efficiency polycarbonate and high-efficiency, high-price collector were developed and tested. A pad humidifier was selected as the most effective equipment to humidify the solar heated air in the desalination plant and its performance was compared with a U-tube spray humidifier. A tube-fin type heat exchanger was used as a dehumidifier and its performance was predicted by simulation program. Out of 40 desalination plants taken for the study, five stages plant delivered the best result.

A theoretical study was made by Marmouch et al. [51] on the effect of a cooling tower on a solar desalination system. By using the humidification–dehumidification principle a prototype unit was designed. The optimal configuration for maximum freshwater production (more than 37 l/m^2/day) was produced by the system with six stages of heating–humidification of the air with the addition of a cooling tower.

Zhani et al. [52] experimentally investigated a new solar desalination prototype using the humidification–dehumidification principle. The modified desalination system consists of a flat plate solar air collector, a flat plate solar water collector, a humidifier, an evaporation tower and a condensation tower. The payback period of the experimental setup was found as 6776 days. The outlet water temperature was the maximum at midday which was about 55 °C. This increase in temperature is due to the latent heat of condensation. It is useful to recycle this water into the evaporation tower and the humidifier. The experimental results also show that the outlet and the inlet temperatures at different component levels have the same trends as solar radiation and the ambient air temperature has an insignificant effect on thermal performance of the unit.

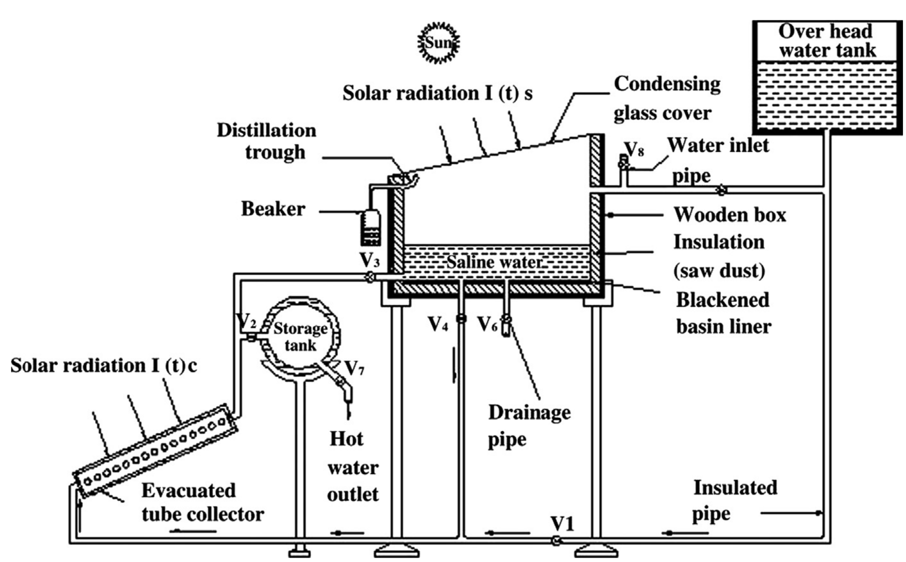

Fig. 7. Utilization of solar water heater in a single basin solar still [48].

2.10. MED/MSF desalination system

Alarcon-Padilla et al. [53] compared the case study of solar desalination by taking three main possibilities into account: (a) Medium temperature solar collectors as a heat source of a Double Effect Absorption Heat Pump (DEAHP) coupled with the Multi-Effect Distillation (MED) unit; such collectors are Parabolic Trough type (PTC), which is one axis-tracking solar collector. (b) Medium temperature solar collectors as direct source of the MED unit in which the solar field and the MED plant are connected by a steam generator. (c) Low Temperature solar Collectors (LTC) connected to MED unit. The results showed that an Absorption Heat Pump (AHP) is able to partially or totally reduce the mass flow rate of seawater cooling to the MED process, thus decreasing the pumping consumption and seawater intake capital cost. The use of an AHP offers a possibility of decreasing the boiling temperature of the last effect of the MED unit, even below the ambient temperature.

Palenzuela et al. [54] developed a simulation to produce 14,400 m^3/day freshwater and 50 MW power for different configurations of Low Temperature Multi-Effect Distillation (LT-MED), Thermal Vapour Compression Multi-Effect Distillation (TVC-MED), coupled with a Concentrating Solar Power (CSP) plant, Reverse Osmosis (RO). The results showed that the combination of a RO and a CSP plant has a better cycle efficiency than the layouts with MED units, though it loses more energy to atmosphere during the cooling process. The coupling of TVC-MED into a CSP is more efficient thermodynamically than the decoupling, and also more economical since it requires a smaller solar field for the same power and water production. The integration of a LT-MED plant into a CSP plant is more efficient from a thermodynamic and economic point of view than the integration of a TVC-MED.

Pinch technology is a graphical method of identifying technically and economically interesting energy efficiency measures. It is based on thermodynamic analysis. Shaobo Hou et al. [55] presented a method of performance optimization of solar Multi-Stage Flash (MSF) desalination process using pinch technology (Fig. 8) when the temperature range is from 30 to 100 °C. The outcome confirmed that the GOR (Gain Output Rate) rests on the working temperature range of MSF and the sum of both the maximum stage temperature difference and pinch point temperature difference. The wide working temperature range of MSF was expected to enhance the GOR, but not pump out the distilled water at middle stages, and also to keep the same stage temperature difference without fluctuation.

2.11. Other methods

Two mathematical models were generated and used to compare the productivity of double effect solar still with a single effect solar still by Al-Hinai et al. [56]. The annual average daily output for single solar still was found to be 4.15 kg/m^2/day while for double-effect solar still it is 6.1 kg/m^2/day representing an increase of 39% over that obtained for a single-effect solar still yield. The depth of the water varies beyond 0.05 m, varying the shallow depth in the bottom tray which tends to result in a higher stilly yield. The cost analysis clearly indicates that a double-effect solar still can produce distilled water at lesser cost than that of a single-effect solar still, and by as much as 15.7%. The shallow water basin, 23° cover tilt angle, 0.1 m insulation thickness, and asphalt coating of the solar still were found to be the optimum design parameters for both solar stills, operating under climatic conditions in Oman.

A new system of solar assisted heat pump desalination (Fig. 9) was designed and fabricated by Hawlader et al. [57]. The major components available in the system are compressor, condenser, evaporator, solar collector, desalination chamber and vacuum pump. The feed water was preheated before being sprayed by the nozzle. The function of the nozzle is to generate droplet in the desalination unit. The compressor speed (1200, 1450 and 1800 rpm) and feed water inlet temperature were the operating variables in the experimental work. The effect of flashing was investigated and feed water flow rate and chamber pressure were fixed with 9.54 kg/h and 0.136 bar respectively. The highest value of performance ratio 1.15 was attained at 1800 rpm. The performance ratio range and COP of the heat pump range lie between 0.77 and 1.15 and 5.0 and 7.0 respectively. The new system produced 88.4% efficiency at maximum compressor speed.

Solar still basins mounted on the roof of greenhouse was made transparent in order to transmit solar radiation to the crop area by Garcia Mari et al. [58]. The ambient temperature reached a maximum of 40 °C, but the crop area was maintained between the temperature limit of 14 and 24 °C by providing ventilation in the present work. Here solar still serves a dual purpose of producing distillate water and acts as a radiation cover for crop area. Installation of solar still decreases the solar radiation in the greenhouse by 52%. The distillation pattern is not similar to the conventional one and the yield obtained by this method is less when compared to the conventional solar still.

Kumar et al. [59] carried out a performance study with different samples such as tap water, seawater and dairy industry waste matter. The solar still productivity was found when still is subjected with and without condensation on the sidewalls. The maximum daily production of the solar still reached 1.4 l/m^2/day for tap water sample, and its efficiency around 30% with corresponding average solar insolation of 28 MJ/day by adopting condensation on the sidewalls.

An endeavor was made by Dwivedi et al. [60] to evaluate the internal heat transfer coefficient of single and double slope passive solar stills in summer as well as winter climatic conditions for three different water depths (0.01, 0.02 and 0.03 m) by various thermal models. It was observed that with the increase in water depth from 0.01 m to 0.03 m there was a marginal variation in the values of convective heat transfer coefficient and annual basis output. The single slope solar still is better (499.41 l/m^2) when

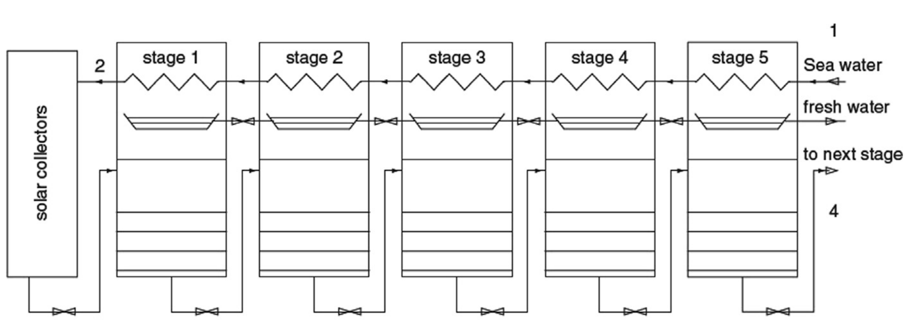

Fig. 8. Sketch of the first five stages of the solar MSF desalination process [55].

compared with a double slope solar still (464.68 l/m^2). The average annual values of the convective heat transfer coefficient for single and double slope solar stills are 1.463 W/m^2 and 1.923 W/m^2 whereas the average annual values of the evaporative heat transfer coefficient for single and double slope solar stills are 8.837 W/m^2 and 8.19 W/m^2 respectively.

El-Sebaii et al. [61] attempted to improve the daily productivity of the single effect solar stills, a single-slope single-basin solar still integrated with a Shallow Solar Pond (SSP) to perform solar distillation at a relatively high temperature. The end result showed that the annual average of daily productivity with the SSP is found to be higher than that of the still without the SSP by 52.36% and its daily efficiency for the system with the SSP is higher than that without the SSP by 43.80%.

The major parameters which govern the productivity of the solar still are brine depth, solar radiation and cover tilt angle. Abdul Jabbar et al. [62] framed four important correlations by using the least square method.

The still productivity influenced by brine depth alone is up to 33%.

$$\text{For brine depth, } y = 3.884e^{-0.0458(d)} \tag{1}$$

where (y) is the productivity in (l/m^2/day) and (d) is the brine depth in (cm).

$$\text{For solar radiation, } y = 0.0036(I)^2 + 0.0701(I) + 0.2475 \tag{2}$$

where (y) is the productivity in (l/m^2/day) and (I) is the solar radiation in (MJ/m^2/day).

The productivity of the still is directly related to the intensity of the solar radiation received. The productivity value of 63% solely depends upon the cover tilt angle.

$$\text{For cover tilt angle, } y = -0.0025(a)^2 + 0.1562(a) + 0.843 \tag{3}$$

where (y) is the productivity in (l/m^2/day) and (a) is the cover tilt angle (degree).

The still yield was enhanced by 20% due to the addition of dark soluble dye to the brine.

$$\text{For using dyes, } y_D = 1.2122(y)^{1.0467} \tag{4}$$

where (y_D) is the productivity with dye and (y) is that without the dye, both in (l/m^2/day).

The solar desalination performance, design and optimization calculation and modeling program was worked out under Matlab/SimuLink by Nafey et al. [63]. The desalination plant components such as heat exchangers, flash chambers, evaporators, pumps, steam ejectors, compressors, reverse osmosis membranes, and pipes are modeled and stored as blocks in the SimuLink visual library. Calculations such as energy, exergy and thermo-economics are done by the plant designer with the help of the program which aids to do some modifications of an existing plant or to develop the conceptual design of new configurations. The designed code can be converted into the programming languages such as Visual basic, Visual C, Visual C++, and Visual Fortran and the plant variables are also transformable.

Reddy et al. [64] developed a novel multi-stage evacuated solar desalination system by utilizing latent heat recovery. Due to the thin

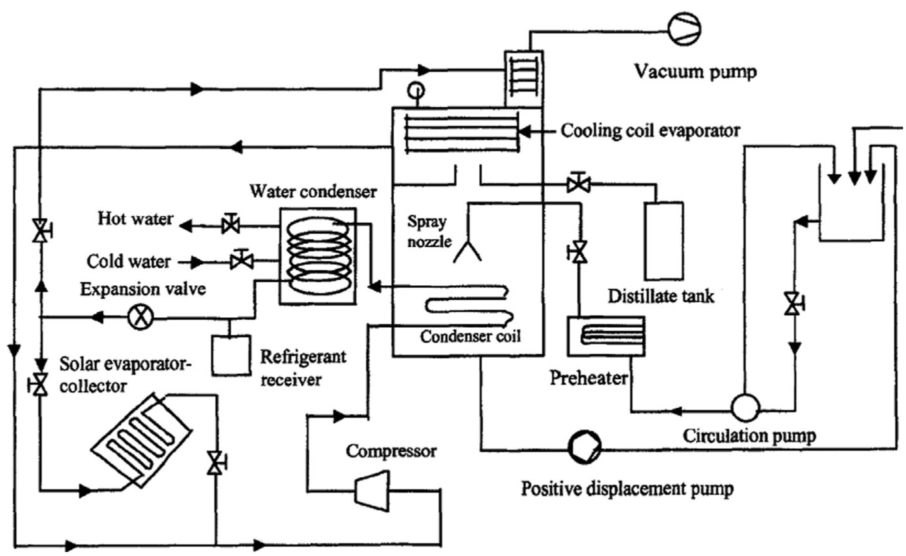

Fig. 9. Heat Pump assisted solar desalination [57].

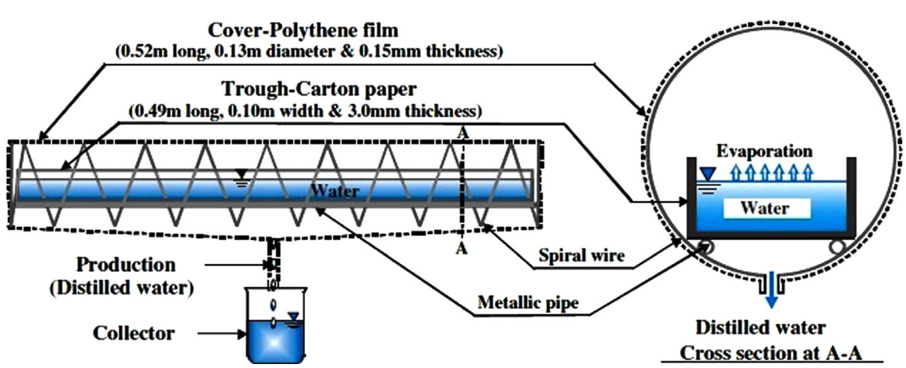

Fig. 10. Schematic diagram of the new Tubular Solar Still [65].

layer of water in the stages, the distillate yield increases with a decrease in mass flow rate from 150 kg/m^2/day to 55 kg/m^2/day. Further decreasing the mass flow rate from 55 kg/m^2/day to 30 kg/m^2/day, the distillate yield decreases which is due to the decrease in stage temperature and temperature difference between the stages. The optimum design conditions gave a maximum yield of 28.04 kg/m^2/day and a minimum of 13.33 kg/m^2/day. The freshwater needs of rural and urban communities in the range of 10–30 kg/m^2/day can be fulfilled by the multi-stage solar desalination system.

Ahsan et al. [65] described the design, fabrication cost and water production analysis of the old Tubular Solar Still (TSS) and the improved one. A highly durable polythene film was adopted as the cover of the improved TSS (Fig. 10) which is replaced from vinyl chloride sheet. The outcome showed that the fabrication cost and weight of the improved TSS were reduced by 92% and 61% compared to those of the old one, respectively. The average cumulative evaporation and condensation mass transfer coefficients were about 0.045 m/s and 0.03 m/s, respectively. The average cumulative condensation heat transfer coefficient was about 305 W/m^{2}K, which was 77% of that of evaporation.

Fig. 11. Schematic diagram of inverted absorber solar still [67].

3. Effect of design parameters on solar still performance

Tiwary et al. [66] experimented various designs of solar desalination systems and concluded that the multiwick solar still is the most economic and efficient one. The results show that the conventional solar still made of concrete with black fiber reinforced coating from inside is suitable for a large scale system with capacity more than 1000 l/day. For a small scale system with capacity less than 1000 l/day, the fiber reinforced plastic multiwick solar still is appropriate.

An experimental study of Inverted Absorber Solar Still (IASS) and single slope solar still at different water depth and Total Dissolved Solid (TDS) was carried out by Dev et al. [67]. The schematic diagram of inverted absorber solar still is shown in Fig. 11. An inverted absorber solar still with a curved reflector under the basin of solar still is used to heat the basin from its bottom surface also. The comparative performance of both the solar stills are analyzed at the water depths 0.01, 0.02 and 0.03 m for seawater and for the prepared water of different TDS values (9.5 g/l and 38 g/l) at 0.01 m. The result shows that the maximum optimized water depth can be taken as 0.03 m for the IASS at which the addition of reflector under the basin does not affect its performance considerably in comparison to that of the single slope solar still.

Solar still requires heated water for increased evaporation. An active solar thermal system "Evacuated Tubular Collector (ETC) integrated solar still" has been analyzed for its annual experimental performance for the composite climatic condition of New Delhi, India, by Dev et al. [68]. The modified system can produce 630 kg/m^2 year of distilled water, compared to the amount of 327 kg/m^2 year yielded from a single slope solar still. The maximum overall thermal efficiency of the still has been found to be 30.1% and the annual average has been found to be 21.3%.

The performance of a solar still with different size screens placed in the basin was studied experimentally by Bassam et al. [69]. The increase in daily production of the still was from 11% to 103% compared with an identical still without screens under the same conditions. The effects of screen color, position, number of screens, side wall color, and dye in the basin water were also investigated. An attempt to simulate the new configuration with a simple extension of previous mathematical models for a still without a screen was not successful.

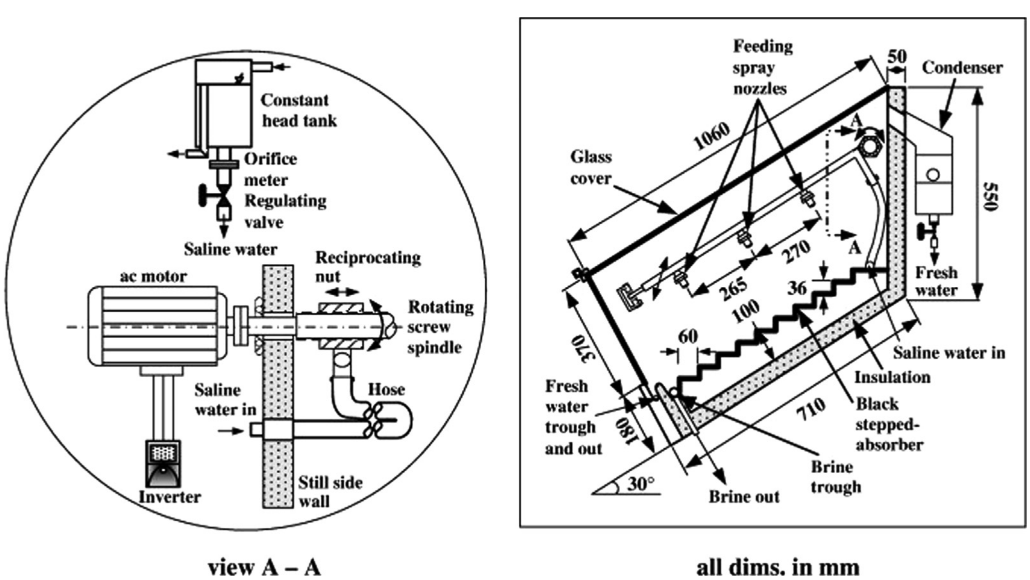

Fig. 12. Schematic diagram of a reciprocating spray feeding system [70].

El-Zahaby et al. [70] introduced a new approach that allows governing the water depth as a desired thin re-established film of saline water in a particular manner in the solar still. This has been achieved by feeding the saline water into the still through a controlled transverse reciprocating spraying system in the form of fine droplets to spread on the top surface of a corrugated steeped shape absorber of the solar still. The schematic diagram of a reciprocating spray feeding system for the solar still is shown in Fig. 12. By the spray feeding system, within 10 h working period, 6.355 l/m^2 at a high efficiency of 77.35% was gained.

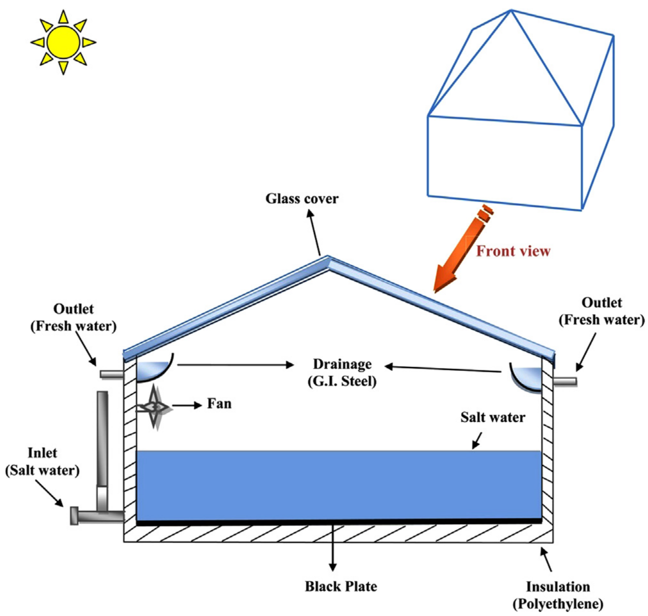

Fig. 13. Schematic diagram of a pyramid-shaped solar water purification system [71].

The exergy and economic analysis of pyramid-shaped solar desalination system was done by Kianifar et al. [71] in active (with fan) and passive cases (without fan). The schematic diagram of pyramid shaped solar desalination system is shown in Fig. 13. The results show that during summer, active unit has higher exergy efficiency than passive one while in winter there is no considerable difference between the exergy efficiency of the units. Results also reveal that the exergy efficiency is higher when the water depth in the basin is lower. Finally, the economic analysis shows a considerable reduction in production cost of the water (8–9%) when the active system is used.

Abdullah [72] fabricated stepped solar still at a tray depth of 5 mm and achieved 30.4% higher efficiency than the conventional solar still. The schematic diagram of the stepped solar still incorporated with solar air heater is shown in Fig. 14. The hot air from a solar air heater to the stepped still (Technique 1) increases the saline water temperature and the glass cover cooling (Technique 2) enhances the temperature difference between the saline water and outer glass temperature. By techniques 1 and 2 the efficiency increases by 65% and 53% respectively. Incorporating both techniques in stepped solar still, the efficiency increases by 112%.

A new design of solar still with a hemispherical top cover for water desalination (with and without flowing water over the cover) was fabricated by Arunkumar et al. [73]. The surface area of the hemispherical solar still is greater than a single slope solar still. The schematic diagram of the hemispherical solar still is shown in Fig. 15. The variation of distilled yield is in the range of 3.58–3.68 l/m^2/day without cooling and 4.18–4.2 l/m^2/day with

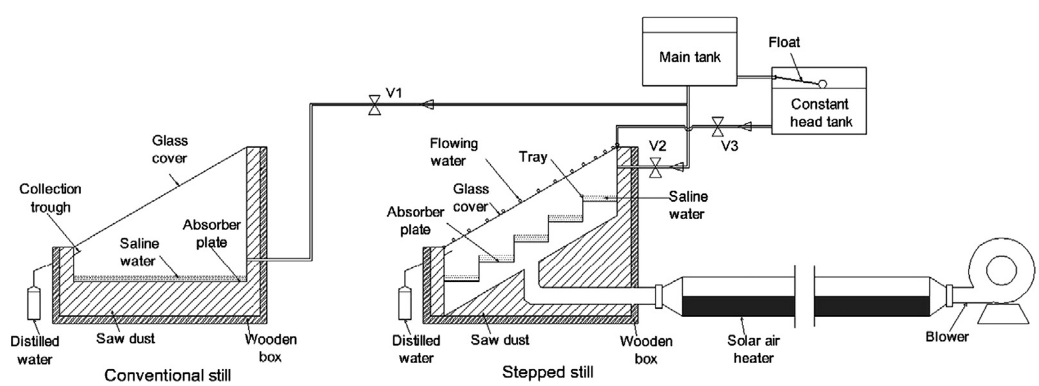

Fig. 14. Schematic diagram of the stepped solar still incorporated with solar air heater [72].

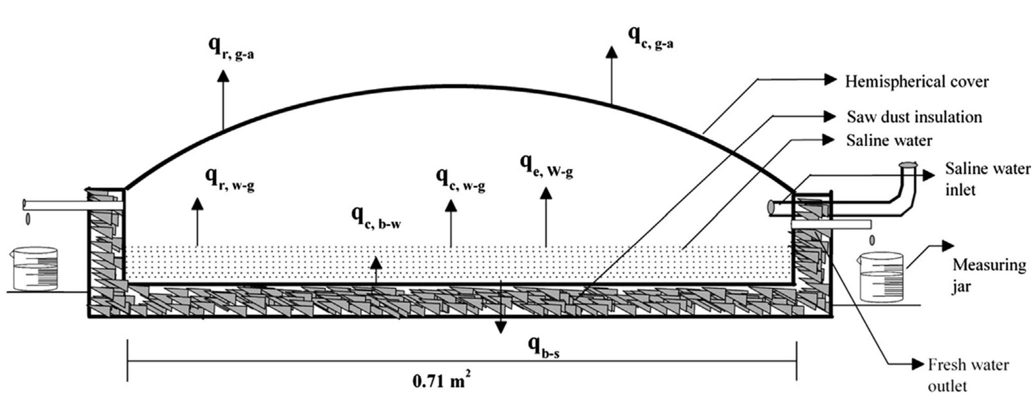

Fig. 15. Schematic diagram of the hemispherical solar still [73].

cooling. The daily average water productivity is increased from 3.66–4.2 l/m^2/day for a fixed flow rate of 10 ml/min of water fed.

Bakhtiari Ziabari et al. [74] used 7 mm wires to provide an even water distribution and increase the residence time on the absorber surface. The schematic diagram of the cascade solar still is shown in Fig. 16. The thin layer of water on the absorber plate helped the evaporation of brackish water and improves the still productivity. The average freshwater production for the modified cascade solar still is around 6.7 lit/day m^2, which shows 26% increase in comparison to conventional solar still.

The modified stepped solar still with trays (5 mm depth × 120 mm width) was fabricated and investigated by Omara et al. [75]. The schematic diagram of modified stepped solar still with internal reflector is shown in Fig. 17. The productivity of modified stepped solar still with reflectors is higher than that for conventional still by 75%. The daily efficiency of modified stepped with solar still internal reflectors and conventional solar stills is approximately 56% and 34% respectively.

4. Effect of meteorological parameters on solar still performance

By the mercy of nature, meteorological parameters cannot be controlled by human beings. The performance of the still was better when there were showers of small duration and then the sky became clear. This can be achieved by making a thin layer of water to flow over the glass cover. An attempt was made to compare the experimental performance of the still prepared with the fiber reinforced plastic under different modes of operation by

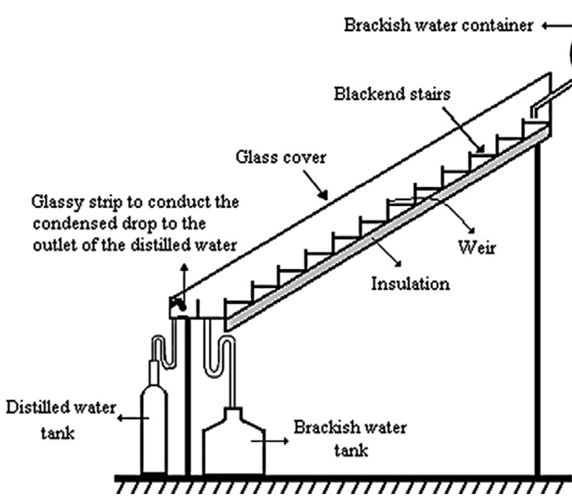

Fig. 16. Schematic diagram of the cascade solar still [74].

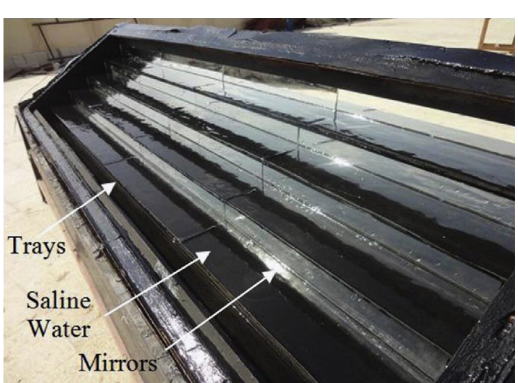

Fig. 17. Schematic diagram of stepped solar still with internal reflectors [75].

Rai et al. [76]. The effects of water mass in the basin, salinity of water, film distillation, thermosyphon and forced circulation of basin water were studied. The salient outputs from the experimental results are that the addition of salt increases the surface tension and hence decreases the rate of evaporation. The forced circulation mode operation yield is 50% more than the thermosyphon mode and 120% more than conventional solar still.

The effect of orientation on the performance of the solar desalination system was studied by Singh et al. [77] for Delhi's climatic conditions. The instantaneous thermal efficiency increases with an increase of inclination due to the increase of solar radiation on the inclined surface. Among the glass cover inclination of 25°, 40°, 55° and 70°, the maximum yield of a double slope solar still was attained at 55° glass cover inclination during winter period.

Solar radiation is one of the meteorological parameters and it depends upon the latitude. Monthly and annual performances of active and passive solar stills were studied for five weather stations like Chennai, Jodhpur, Kolkata, Mumbai and New Delhi by Singh et al. [78]. The geographical parameters of five stations Chennai (13.00° N, 80.18° E), Jodhpur (26.30° N, 73.02° E), Kolkata (22.65° N, 88.45° E), Mumbai (19.12° N, 72.85° E) and New Delhi (28.58° N, 77.20° E) were taken for numerical computations. The results obtained are (i) the annual yield is at its maximum when the condensing glass cover inclination is equal to the latitude of the space and (ii) the optimum collector inclination for a flat plate collector is 28.58°.

The glass cover inclination of single slope solar still coupled with flat plate collector was varied from 15° to 45° for Delhi's climatic conditions by Kumar et al. [79]. It was found that the optimum glass cover inclination is 15° and for maximum annual yield, the optimum collector inclination for a flat plate collector is 20°.

The experiments were conducted in Jordan by Akash et al. [80] on a solar still with various cover tilt angles of 15°, 25°, 35°, 45° and 55°. An optimum tilt angle for water production was found to be 35°. The effect of the salinity of water on solar distillation was studied and it was found that water production decreases with salinity.

Tripathi et al. [81] evaluated the performance of the solar still by using the concept of solar fractionation by using AUTOCAD 2000. The north wall height was taken as 21.5, 41.5, 61.5, 81.5 and 101.5 cm. The change in the height of the north wall for a given basin area and the width of the solar still for a given height of the solar still affects the daily output. Due to the increase in losses from the solar still enclosure to ambient air, the daily output decreases with the increase in the width of the solar still.

Zurigat et al. [82] attained increase in the productivity by more than 50% by increasing the wind speed from 0 to 10 m/s. The thickness of water on top of the first glass cover and the mass flow rate of water going into the second effect have a marginal effect on the productivity of the regenerative still. The performance of the regenerative still is evaluated by comparison with the performance of the conventional still under the same weather conditions.

El-Sebaii [83] studied the effect of wind speed on the daily productivity of some designs of basin type and vertical solar stills by computer simulation. The value of wind velocity is independent of the still shape and heat capacity of the brine. The wind velocity is more effective in summer and at higher water masses and it was found to be 10 and 8 m/s on typical summer and winter days, respectively. It was found that productivity increases with the increase of wind speed up to a typical velocity beyond which the increase in productivity becomes insignificant.

5. Discussion

The comparative study of performance improvement techniques used in solar stills and their results are represented in Table 1.

Table 1
Comparative study of performance improvement techniques used in solar still.

Sl. no.	Author (s)	Modification/tools used	Observations in experiment	Results
1	El-Sebaii et al. [18]	Baffle suspended absorber plate	18.5–20% productivity increased	Preheating time for evaporating water is minimized with the adoption of suspended absorber plate
2	Naim et al. [19]	Charcoal particle	15% enhancement in productivity	Charcoal particle act as a good absorber medium.
3	Zeinab et al. [20]	Packed layer	5–7.5% productivity improvement.	A packed layer of glass ball helps the heating operation of still water throughout daytime and after sunset, to increase the freshwater productivity.
4	Voropoulos et al. [21]	Integration of storage tank	Productivity increases with increase in saline water temperature	The implementation of storage tank is not only to increase saline water temperature; but also to increase the temperature difference between saline water and glass temperature.
5	Naim et al. [22]	Phase Change Materials (PCM)	36.2% still efficiency was achieved when PCM's used.	Emulsion of paraffin wax, paraffin oil and water mixture used as an energy storage material.
6	Nafey et al. [23]	Black rubber and Gravel	Distillate Output is 20% improvement from 10 mm thickness black rubber and 19% increased from 20–30 mm gravel.	Compare to black rubber, gravel absorbs and releases solar energy in a fast manner.
7	Akash et al. [24]	Black rubber mat, black ink and black dye	38%, 45% and 60% enhanced productivity derived by the usage of black rubber mat, black ink and black dye respectively.	Black dye absorbing ability is higher than that of black ink and black rubber mat.
8	Sakthivel et al. [25]	Jute cloth	20% yield capacity increases and 8% more efficiency compared to conventional solar still	The latent heat of condensation available between the saline water and glass cover is effectively used by jute cloth.
9	El-Sebaii et al. [26]	Sand used as a sensible heat storage medium	By the addition of 10 kg of sand the daily productivity and efficiency gets increased to 4.005 kg/m^2 day and 37.8%.	The daily productivity and efficiency of the still decreases with increasing the mass of the sand and thermal conductivity of the basin liner.
10	Abdallah et al. [27]	Absorbing materials	Coated metallic wiry sponges – 28%, Uncoated metallic wiry sponges – 43%, Volcanic rocks – 60% more productivity than conventional system.	The impressive good properties such as absorptivity, permeability and extinction of metallic wiry sponges made to use it as an absorbing material in solar still.
11	Tiwari et al. [28]	Thermal analysis was carried out to optimize glass cover inclination to get maximum yield.	Due to the increase of inclination in summer and winter a significant reduction in evaporative heat transfer co-efficient was observed. The optimum inclination depends upon location and glazing material.	The yield increases with increase of inclination in winter and vice-versa in summer.
12	Abdul Jabbar [29]	The effect of cover tilt angle on productivity was reviewed.	The salient output from the research is that the increase of the tilt angle results in increased thermal losses from the cover and decrease in the yield because of increased reflected radiation	A relation between the cover tilt angle and productivity of simple solar still in various seasons is established together with a relation between the optimum tilt angle and the latitude angle
13	Al-Kharabsheh and Yogi Goswami [30]	The atmospheric pressure and gravity were used to create a vacuum distillation.	Productivity of conventional system—3–4 kg/m^2/day. Modified system – 6.5 kg/m^2/day.	At a water depth of 0.04 m, the maximum collector outlet temperature is equal to 61.2 °C and the accumulated output for water is about 1.3 kg and the pressure reaches a maximum value of about 4.7 kPa absolute.
14	Fathi Nassar et al. [31]	Solar desalination system working on the basis of evacuation.	303% increased productivity and performance ratio 900% higher than roof-type desalination system.	The solar intensity concentration was done by concave mirror and the experimental model consists of elliptical, metallic container located in the focus of concave reflector.
15	Maroo and Yogi Goswami [32]	Theoretical analysis was made for single stage and two stage solar driven flash desalination system based on passive vacuum generation	The system uses the natural forces of gravity and atmospheric pressure to create a vacuum.	Case I: Constant temperature heat source, Productivity and Performance Ratio for Single stage system – 11.31 kg and 0.746. Double stage system – 13.9 kg and 1.42. Case II: Solar still with collector, Single stage system – 5.54 kg and 0.748. Double stage system – 8.66 kg and 1.35
16	Kalidasa Murugavel [33]	Different wick materials and Fins	The aluminum rectangular fin covered with cotton cloth and arranged in length wise direction was more effective.	Light jute cloth, sponge sheet, coir mate and waste cotton pieces also experimented.
17	Kabeel [34]	Pyramid shaped top surface with four glass covers	Black paint coated jute wick is used to increase the evaporative surface area.	Modified still productivity – 4.0 l/m^2 and 45% efficiency
18	Janarthanan et al. [35]	Floating cum tilted wick solar stills	The efficiency of the closed-cycle system is maximum at low flow rate of water.	The open cycle system efficiency variation depends upon heat transfer coefficient from the wick surfaces to ambient and relative humidity.
19	Hiroshi Tanaka [36]	Tilted wick solar still with external flat plate reflector	The inclination angle of the reflector would be less than 25° throughout the year.	The daily amount of distillate can be increased by inclining the reflector backwards in winter and forwards in summer.
20	Abdul Jabbar and Hussein [37]	Solar still with internal and external reflector	The most productive solar still in winter is a still with cover angle of 20° and an internal and external reflector inclined at 20° and its productivity around 2.45 times that of simple still with no reflectors.	The daily yield of the still with no reflectors would remain almost the same at any glass cover angle.

Table 1 (*continued*)

Sl. no.	Author (s)	Modification/tools used	Observations in experiment	Results
21	Garcia-Rodriguez et al. [38]	Multi-stage flash plant with performance ratio of 10 and coefficient of heat pump 2.	The stationary solar still performance was also compared with a one axis sun tracking system coupled with heat pump.	The percentage increase of freshwater production of direct steam generation compared to conventional parabolic trough collector lies between 18–32%.
22	Abdallah et al. [39]	(i) Reflective mirrors on all interior sides (ii) Step wise basin (iii) Sun tracking system	(i) Reflective mirrors – 30%. (ii) Step wise basin – 180% (iii) Sun tracking system – 380% enhancement in productivity.	Reflective mirrors are used to reduce the heat lose. Step wise basin causes 40% increase in surface area and sun tracking system is used to sense the direction where the solar intensity is maximum
23	Abdallah and Badran [40]	Sun tracking system	22% improved productivity and 2% improvement in overall efficiency.	Sun tracking system used to increase the water temperature which leads higher productivity.
24	Sahoo et al. [41]	Blackened base liner with thermocol insulation	A blackened base liner with bottom and side thermocol insulation of 20 mm thickness gave 6.05% more.	The fluoride reduction of 92–96% was achieved as compared to untreated samples
25	Badran [42]	Asphalt liner and Sprinkler	29% output increased by asphalt liner and 22% improved by the application of sprinkler.	Asphalt liner performance was compared to the usage of black paint as the liner. Sprinkler increases the temperature difference between glass cover and water.
26	Schwarzer et al. [43]	Solar collector combined with desalination tower.	Modified solar still yield – 25 l/m^2/day which is five times higher than the conventional solar still.	The desalinated water was subjected to laboratory tests and found it was free from coliform group bacteria.
27	Dwivedi and Tiwari [44]	Double slope still integrated with flat plate collector	The double slope active solar still under natural modes (2.791 kg/m^2) gives 51% higher yield in comparison to the double slope passive solar still (1.838 kg/m^2).	The exergy efficiency of double slope active solar still is higher than the exergy efficiency of double slope passive solar still.
28	Gude et al. [45]	Two-stage low temperature desalination	The specific energy consumption of the process was 1500 kJ/kg (1500 MJ/m^3) of thermal energy in Puget Sound bay area of the State of Washington.	Desalination plant coupled with low grade flat plate solar collector cost is less than $7/m^3.
29	Gude et al. [46]	Low temperature desalination using solar collector	A solar collector area of 15 m^2 with 1 m^3 of Thermal Energy Storage (TES) volume or 18 m^2 with 3 m^3 of TES volume is required to generate the freshwater.	The estimated cost with TES is $655 higher than the without thermal energy storage system.
30	D'Antoni et al. [47]	Literature review of Massive Solar – Thermal Collector (MSTC)	The heat transfer and storing phenomena, moisture transfer phenomena and frost formation characteristics were taken.	The MSTC concept applied to Domestic Hot Water (DHW) and Space Heating (SH) demands.
31	Sampathkumar et al. [48]	Evacuated tube collector model solar water heater coupled with solar still	The productivity of the evacuated tube collector coupled solar still was doubled when compared to the simple solar still.	The modification increased the yield by 77%, even if the collector and solar still were coupled only after the storage tank water temperature reached 60 °C.
32	Mohamed et al. [49]	Parabolic trough solar collector with Humidification–dehumidification principle	The collector thermal efficiency value increases with increase of the solar radiation until reach a maximum value and then declined.	The production time reaches a maximum value of about 42%, 37 %, 33% and 29 % during summer, spring, autumn and winter respectively.
33	Efat Chafik [50]	Dynamic simulation program (TRNSYS)	Out of 40 desalination plants taken for the optimization study, five stages plant delivered best result.	The solar energy is used to heat the air stream and then hot air is humidified by seawater, and followed by dehumidification to derive potable water from it.
34	Marmouch et al. [51]	Humidification–dehumidification principle	The system with six stages of heating–humidification of the air, plus a cooling tower is the optimum arrangement.	Maximum amount of freshwater – more than 37 l/m^2/day.
35	Zhani et al. [52]	Humidification–dehumidification principle	The modified desalination system consists of a flat plate solar air collector, a flat plate solar water collector, a humidifier, an evaporation tower and a condensation tower.	The payback period of the experimental setup was found as 6776 days.
36	Alarcon-PadillaandGarcia-Rodriguez[53]	Double Effect Absorption Heat Pump (DEAHP) coupled to the Multi Effect Distillation (MED)	An Absorption Heat Pump (AHP) is able to partially or totally reduce the mass flow rate of seawater cooling to the MED process, thus decreasing the pumping consumption and seawater intake capital cost.	Three main possibilities into account 1. DEAHP coupled with MED 2. Medium Temperature solar Collectors (LTC) connected to MED unit 3. Low Temperature solar Collectors (LTC) connected to MED unit.
37	Palenzuela et. al [54]	Integrated Power and Desalination Plants (IPDP)	System configuration: Low Temperature Multi-Effect Distillation (LT-MED), Thermal Vapour Compression Multi-Effect Distillation (TVC-MED), coupled with a Concentrating Solar Power (CSP) plant, Reverse Osmosis (RO).	The combination of a RO and a CSP plant has a better cycle efficiency than the layouts with MED units .The coupling of TVC-MED into a CSP is more efficient thermodynamically than the decoupling.
38	Hou et al. [55]	Pinch technology	The GOR rests on the working temperature range of MSF and the sum of both the maximum stage temperature difference and pinch point temperature difference.	Pinch technology is a graphical method of identifying technically and economically interesting energy efficiency measures.

Table 1 (*continued*)

Sl. no.	Author (s)	Modification/tools used	Observations in experiment	Results
39	Al-Hinai et al. [56]	Single effect and Double effect solar still	Productivity of single effect solar still - 4.15 kg/m^2/day and Double effect solar still – 6.1 kg/m^2/day.	The shallow water basin, 23° cover tilt angle, 0.1 m insulation thickness, and asphalt coating of the solar still were found to be the optimum design parameters for both solar stills.
40	Hawlader et al. [57]	Solar assisted heat pump desalination	The performance ratio range and COP of the heat pump range lies between 0.77 to 1.15 and 5.0 to 7.0 respectively.	The compressor speed (1200, 1450 and 1800 rpm) and feed water inlet temperature are the operating variables in the experimental work. The new system produced 88.4 % efficiency at maximum compressor speed.
41	Garcia Mari et al. [58]	Roof type solar still	Installation of roof type solar still decreases the solar radiation into the green house by 52%.	Solar still serves a dual purpose of producing distillate water and acts as a radiation cover for crop area.
42	Vinoth Kumar and Kasturi Bai [59]	With and without condensation on the sidewalls	Different samples such as tap water, seawater and dairy industry waste matter performance were analyzed.	By adopting condensation on the side wall – 1.4 l/m^2/day productivity and 30% efficiency was achieved.
43	Dwivedi and Tiwari [60]	Single and double slope passive solar stills	The single slope solar still is better (499.41 l/m^2) as compared with a double slope solar still (464.68 l/m^2).	The convective heat transfer coefficients for single and double slope solar stills are 1.463 W/m^2 and 1.923 W/m^2.
44	El-Sebaii et al. [61]	Solar still integrated with a Shallow Solar Pond (SSP)	52.36 % annual average of daily productivity with SSP higher than without the SSP.	Daily efficiency for the system with the SSP is higher than that without the SSP by 43.80%.
45	Abdul Jabbar et al. [62]	Performance correlations	The major parameters which govern the productivity of the solar still are brine depth, solar radiation and cover tilt angle.	The still productivity influenced by brine depth alone is up to 33%, cover tilt angle alone by 63%. The still yield enhanced by 20% due to the addition of dark soluble dye to the brine.
46	Nafey et al. [63]	Modeling program developed by Matlab/SimuLink	To develop the conceptual design of new configurations in solar desalination Matlab/SimuLink modeling program can be used.	The designed code can able to convert into the programming languages such as Visual basic, Visual C, Visual C++, and Visual Fortran and the plant variables are also transformable.
47	Reddy et al. [64]	Multi – stage evacuated solar desalination	Due to the thin layer of water in the stages, the distillate yield increases with a decrease in mass flow rate. Further decreasing the mass flow rate, the distillate yield decreases.	More suitable for the rural and urban demands in the range of 10 to 30 kg/m^2/day.
48	Amimul Ahsan et al. [65]	old and new Tubular Solar Still (TSS)	Covering material used in Old TSS – vinyl chloride sheet, New TSS – polythene film	The fabrication cost and weight of the improved TSS were reduced by 92% and 61% of the old one, respectively.
49	Tiwary et al. [66]	Multiwick solar still	The solar still productivity lesser than 1000 l/day is considered as small scale system.	Solar still is suitable for – large scale system – concrete with black fiber reinforced coating – small scale system – fiber reinforced plastic multiwick
50	Dev et al. [67]	Inverted Absorber Solar Still (IASS)	An inverted absorber solar still with a curved reflector under the basin of solar still is used to heat the basin from its bottom surface also.	The maximum optimized water depth can be taken as 0.03 m for the IASS.
51	Dev et al. [68]	Evacuated Tubular Collector (ETC) integrated solar still	"Evacuated tubular collector Integrated Solar Still (EISS)" provides both hot water and potable water.	Conventional solar still yield – 327 kg/m^2 year etc integrated solar still yield – 630 kg/m^2 year
52	Bassam et al. [69]	Different size screens placed in the basin	The effects of screen color, position, number of screens, side wall color, and dye in the basin water were also investigated.	The increase in daily production of the still was 11–103% compared with an identical still without screens under the same conditions.
53	El-Zahaby et al. [70]	Transverse reciprocating spraying system used in solar still.	Spraying system approach that allows governing the water depth as desired thin re-established film of saline water on a particular manner in the solar still.	Within 10 h working period 6.355 l/m^2 at high efficiency of 77.35% was gained.
54	Ali Kianifar et al. [71]	Pyramid-shaped solar water desalination system	During summer, active unit has higher exergy efficiency than passive one while in winter there is no considerable difference between the exergy efficiency of the units. The exergy efficiency is higher when the water depth in the basin is lower.	The economic analysis shows a considerable reduction in production cost of the water (8–9%) when the active system is used.
55	Abdullah [72]	Stepped solar still at a tray depth of 5 mm	The hot air from a solar air heater to the stepped still (under steps) increases the saline water temperature and the glass cover cooling technique enhances the temperature difference between the saline water and outer glass temperature.	The efficiency of the solar still 65% and 53% higher achieved by adapting the technique separately and it was 112% over conventional solar still when both the techniques incorporated in the stepped solar still.
56	Arunkumar et al. [73]	Hemispherical solar still	The surface area of the hemispherical solar still is greater than a single slope solar still.	The variation of distilled yield is in the range of 3.58 to 3.68 l/m^2/day without cooling and 4.18–4.2 l/m^2/day with cooling.
57	Bakhtiari Ziabari et al. [74]	Cascade solar still	The thin layer of water on the absorber plate helped the evaporation of brackish water and improves the still productivity.	The average freshwater production for the modified cascade solar still is around 6.7 l/day m^2, which shows 26% increase in compare to conventional solar still.

Table 1 (*continued*)

Sl. no.	Author (s)	Modification/tools used	Observations in experiment	Results
58	Omara et al. [75]	Stepped solar still with trays (5 mm depth × 120 mm width)	The productivity of modified stepped solar still with reflectors is higher than that for conventional still by 75%.	The daily efficiency of modified stepped with internal reflectors and conventional solar stills is approximately 56% and 34% respectively.
59	Rai et al. [76]	The effect of water mass in the basin, salinity of water, film distillation, thermosyphon and forced circulation of basin water were studied.	The performance of the still was better when there were showers of small duration and then the sky is clear.	The addition of salt increases the surface tension and hence decreases the rate of evaporation. The forced circulation mode operation yield is 50 % more than the thermosyphon mode and 120 % more than conventional solar still.
60	Singh et al. [77]	Effect of orientation on the performance	The instantaneous thermal efficiency increases with an increase of inclination due to the increase of solar radiation on the inclined surface.	The maximum yield of a double slope solar still was attained at 55° glass cover inclination during winter period for Delhi climatic conditions.
61	Singh et al. [78]	Monthly and annual performances of active and passive solar stills were studied for five weather stations.	The solar radiation is one of the meteorological parameter and it various depends upon the latitude.	(i) The annual yield is at its maximum when the condensing glass cover inclination is equal to the latitude of the space. (ii) The optimum collector inclination for a flat plate collector is 28.58°.
62	Kumar et al. [79]	Optimization of glass cover and collector inclination	The glass cover inclination of single slope solar still coupled with flat plate collector was varied from 15° to 45° for Delhi climatic conditions.	Optimum glass cover inclination – 15°. Flat plate collector inclination – 20°
63	Akash et al. [80]	Solar still with various cover tilt angles of 15°, 25°, 35°, 45° and 55°	An optimum tilt angle for water production was found to be 35°.	The effect of the salinity of water on solar desalination was studied and it was found to be water production decreases with salinity.
64	Tripathi et al. [81]	Solar fractionation by using AUTOCAD 2000	The change in the height of the north wall for a given basin area and the width of the solar still for a given height of the solar still affects the daily output.	Due to the increase in losses from the solar still enclosure to ambient air, the daily output decreases with the increase in the width of the solar still.
65	Zurigat et al. [82]	The effect of wind speed on the daily productivity of solar still.	The thickness of water on top of the first glass cover and the mass flow rate of water going into the second effect have marginal effect on the productivity of the regenerative still.	Attained increase in the productivity by more than 50% by increasing the wind speed from 0 to 10 m/s.
66	El-Sebaii [83]	The effect of wind speed on the daily productivity of solar still.	The value of wind velocity is independent of the still shape and heat capacity of the brine.	The productivity increases with the increase of wind speed up to a typical velocity beyond which the increase in productivity becomes insignificant.

5.1. *Inferences from the review work on solar still performance*

This work reviews the studies and developments of solar stills. The results from the preceding work done clearly show that the enhancement of solar still performance differs greatly for different techniques due to different experimental conditions. There are still some problems and challenges on the design of solar still not being clearly analyzed for its performance improvement. The present research of improvement technique of solar still is inadequate and needs further development. The research work under the same climatic conditions for different basin types solar stills made up of different basin materials may give a cost effective and optimum performance solar still.

6. Conclusions

Various research works done on solar still to improve its productivity are reviewed. The essential points are highlighted below.

- Any heat storing method in solar desalination process is effective as compared to that without heat storage.
  - By the introduction of baffle suspended absorber plate the free surface area of water is increased which gives 18.5–20% more productivity.
  - Charcoal particle acts as a good absorber medium which produces 15% more yield.
  - The mixture of paraffin wax, paraffin oil and water added with Al turnings used as a special phase change material increases the productivity to the maximum value of 851 ml/m^{2}h.
  - The productivity was enhanced by 38%, 45% and 60% respectively when absorbing materials like black rubber mat, black ink, and black dye were used.
  - The regenerative still with jute cloth gives a cumulative yield of 20% which is higher than that of conventional solar still.
  - By the addition of 10 kg of sand as sensible heat storage medium the daily productivity and efficiency are increased by 1.153 kg/m^2/day and 10.8%.
  - The yield was increased by 28%, 43% and 60% respectively when absorbing materials like coated metallic wiry sponges, uncoated metallic wiry sponges and volcanic rocks were used.
- The annual yield of the solar still is maximum when the condensing glass cover inclination is equal to the latitude of the place.
- The solar still productivity increased when vacuum was applied.
  - The atmospheric pressure and gravity were used to create vacuum distillation which gives 2.5 kg/m^2/day more yield compared to the conventional solar still.
- Among the different wick materials, light black cotton cloth was the most effective which gives higher production.
  - The average distillate productivity of the pyramid shaped top surface with four glass covers during the 24 h time is about 4 l/m^2 and its efficiency reaches about 45%.
- The sun tracking system is more effective than fixed system and it is capable of enhancing the productivity of the still.
  - The use of sun tracking system increased the productivity and overall efficiency by 22% and 2% respectively.
- The introduction of asphalt as basin liner increases the output by 29% when compared to the usage of black paint as the liner.

- The solar still coupled with solar collector, solar pond, cooling tower and additional condensation on sidewalls of the basin shows better performance.
  - Solar collector combined with desalination tower yield was 25 l/m^2/day which is five times higher than the conventional solar still.
  - The productivity of the evacuated tube collector coupled solar still was increased by 77% compared to the conventional solar still.
  - The stepped solar still incorporated with solar air heater and glass cover cooling technique productivity was increased by 112%.
- Integrated Power and Desalination Plants (IPDP) must be developed to use solar energy for solving future energy and water problems.

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